"Investigating cold based summit glaciers through direct access to basal ice: A case study constraining the maximum age of Chli Titlis glacier, Switzerland" by Pascal Bohleber et al.

- Response to reviews -

Please note:

- ***Author's responses to the referee's comments are in blue***
- ***Changes in the corresponding revised manuscript are highlighted in red***
- ***All line numbers in "Changes to manuscript" refer to the new revised version***
- ***All new references can be found in the new manuscript***

Response to referee #2, R. Waller

General comments

I agree with the first referee that this paper presents a series of interesting findings from a summit glacier in Switzerland that suggest that a cold-based thermal regime has been persistent at this site resulting in the preservation of the basal ice for c. 5,000 years. The paper is therefore clearly appropriate for publication within The Cyrosphere although I think there are areas that would benefit from further work.

We thank the referee for his comments and in particular for bringing our attention to the importance of a detailed description of the ice facies. Although the authors did not have a detailed background in geology we have consulted the respective literature and our visual analysis of the stratigraphy. Based on this further investigation we have added to the revised manuscript, in particular Table 2 giving an overview on the macroscopic ice characteristics.

Areas for improvement

Agree firstly with the comments of the first referee - particularly the need to include a map of the study site that indicates the location and setting of the glacier and the tunnel. The paper focuses on the examination of basal ice at the site but is unclear whether the use of the term “basal” is used simply to refer to its position at the base of the glacier or in its glaciological sense (ice which is produced at and interacts with the bed; e.g. Knight, 1997). Either way, I would recommend that the authors consult some of the relevant literature to inform their description and interpretation of the ice examined in this study. On a related note, I would like to see a more detailed description of the ice facies observed within the tunnel within section 3 to support the more detailed ice petrography reported in section 3.4 (see for example Hubbard & Sharp, 1995). The impact of the work would be enhanced if greater emphasis was given to the broader context of the work and its key findings

within both sections 1 and 5. What is the wider palaeoclimatological and palaeoglaciological significance of the preservation of ice 5,000 years at this altitude? Section 4.5 in particular would benefit from a clearer structure to help emphasise and explain the key points.

We appreciate these valuable suggestions and have tried to integrate them in the revised manuscript. Specifically, we have compiled a new figure 1 showing a location map. We have also consulted the suggested literature regarding ice facies, and now include these references in a more in-depth discussion of this point. We have added a respective table (Table 2) with an overview of the main stratigraphic features at each sampling site. We also tried to add more discussion regarding the wider paleoclimatological and paleoglaciological significance of our results. At the same time we would like to point out the pilot character of this work and believe that the full paleoclimatic implications of constraining the maximum age of these summit glaciers will fully unfold after combining results from several sites and comparing them with other proxy evidence in more detail. This is already part of our ongoing investigation.

As an additional comment, we now realize that the use of the word "basal" in the original version of the manuscript was not sufficiently clear and may have caused some confusion. We intended to refer to the lowermost, hence potentially oldest sections of the glacier. While this includes the "basal layer" in a strict glaciological sense, we actually referred to a much larger section of ice above the glacier base, i.e. that becomes accessible at Chli Titlis through the ice cave.
We thank the referee for pointing out this ambiguity and have clarified the manuscript accordingly.

Changes to manuscript: P4, L4-5: Clarified the use of the term "basal" vs "lowermost".

Minor comments

P1 - Abstract - Highlight the primary research question this research is aiming to address. Feel this will help to establish its wider context and significance.

Thank you for the suggestion. We decided to reword part of the abstract to point out our primary research questions more clearly.

Changes to manuscript: P1, L6ff: Reworded abstract.

P1 - L8/9 - Explain what is meant my “standard glaciological tools”.

We have removed this part in the reworded abstract version and feel that our approach is presented in a more explicit way now, including specifically stating what tools were used in the study.

P1 - L9 - Clarify what is meant by the use of the term “sophisticated”.

We have reworded this part as "state-of-the-art micro-radiocarbon analysis". The primary challenge compared to conventional radiocarbon dating methods is that glacier ice comprises extremely low carbon concentrations, requiring a great deal of sophistication in sample preparation and analysis.

Changes to manuscript: P2, L22ff. We have clarified this point in the Introduction and also include a new reference to the recent paper by Hoffmann et al. (2017), describing the employed technique in detail.

P1 - Section 1 - Explain more explicitly why cold-based thermal conditions are of such importance - i.e. warm-based conditions and basal melting lead to the loss of the oldest ice - impossible therefore to date onset of most recent phase of glaciation.

Thank you for the suggestion. We have added a respective statement to clarify.

Changes to manuscript: P2, L6-8. Statement added.

P1 - L19/20 - Provide the approximate altitudinal ranges for “uppermost summit ranges” and “lower altitudes”.

Changed accordingly.

P2 - L4 - Basal temperatures persistently below the pressure melting point?

Yes, thank you- changed accordingly.

P2 - L5 - Clarify what is meant by “glacier buried tree parts” - re-word.

Changed accordingly.

Changes to manuscript: P2, L12-13: " trees formely buried by glacier advances"

P2 - L8/9 - Give greater emphasis to this key broader aim of the research (e.g. could be presented at the start of the final paragraph in this section) and provide a little more explanation on how the paper will help to realise this aim.

We appreciate the suggestion and, in an attempt to give greater emphasis on the broader context of this research, have restructured the middle part of the introduction.

Changes to manuscript: P2, L5-29. Restructured part of Introduction.

P3 - L6 - “as well at around...”

What we intend to say here is " report sub-zero bedrock temperature *and* temperatures around -1 deg C..."

Changes to manuscript: P4, L18-19. Changed statement.

P3 - L8 - What attribute provides the layering? Variations in bubble content, sediment concentration? As mentioned earlier, providing a more detailed description of the characteristics of the basal ice here and within section 4 would be helpful.

At this instance we are referring to the earlier study by Haeberli et al. (2004). The authors do not mention any details regarding the nature of the layering. However, following the referee's suggestion we have added more detail regarding the stratigraphy of the three sampling sites. We have included this description in section 3.4 (see comment below), and have also added a new table (Table 2) summarizing the main characteristics. We then refer to these characteristics again in section 4.

Changes to manuscript: P7, L1-11. Included description of visual stratigraphy in section 3.4.

P3 - L25 - Reword from “third spot” to “third profile”.

Changed accordingly.

P3 - L28/29 - Use of the term “clear” here needs further clarification. Again - highlights need to include a section (maybe initially in section 2) that provides a more detailed description of the basal ice facies observed and clarification of the significance of the use of the term “basal”.

We clarified that "clear" here refers to being entirely bubble-free. We have included a full description of the visual stratigraphy in section 3.4.

Changes to manuscript: P7, L1-11. Added full description of the visual stratigraphy to section 3.4.

P4 - Figure 1 - Include scale in Figure 1A. P4 - L4 - “20cm vertical intervals”

The original sketch in Figure 1A was not to scale. However, we have added a new Figure 1 showing the glacier site (an a zoom-in on the tunnel location) as orthophotos, thus including GPS coordinates (Swiss grid) for scale.

Changes to manuscript: Added new Figure 1 with orthophotos.

P5 - Section 3.2 - Where the stable isotope measurements taken from all the ice blocks? (Fig 2 suggests not)

Yes, in fact isotope data from block 2-5 in profile 2 is missing. The other profiles have continuous isotope measurements (at least one measurement per block). We have added information to the text to clarify this.

Changes to manuscript: P6, L2. Added Statement to clarify no data is available for block 2-5.

P5 - L3 - "The outermost 10 cm of each block exposed to the tunnel was removed"

Changed accordingly.

Changes to manuscript: P5, L7-8.

P5 - Section 3.3 - Which blocks were used for the radiocarbon dating?

We provide this information in Table 1, first column. We have slightly rearranged the text in the column to clarify this, now separating block number and combustion temperature.

Changes to manuscript: Table 1

P6 - Section 3.4 - Include a description of the macroscopic characteristics of the ice facies investigated here - ideally refer to an ice facies classification scheme. Explain why the clear ice facies was specifically targeted for analysis.

We appreciate the suggestion and have added a new paragraph to this section describing the macroscopic characteristics of the ice facies. We have also added a new table (Table 2) to summarize the characteristics following the classification scheme of Hubbard et al. (2009). The clear ice facies was not specifically targeted, but rather a result of the search for different basal ice characteristics, i.e. visual differences w.r.t profile 2.

Changes to manuscript:

- P7, L1-11: Added new paragraph.
- Added new Table 2.

P6 - Section 4.1- It's worth emphasising here that the measured temperatures are significantly lower than those previously recorded by Haeberli.

Thank you, we added a respective remark to this section. We suspect this may be connected to the artificial cooling installed in recent years.

Changes to manuscript: P8, L14: Added statement.

P7 - L7 - Equilibriation?

Yes, referring to the time needed for the sensors to be in equilibrium with the ambient ice temperature.

Changes to manuscript: P8, L19: "limited time for establishing equilibrium".

P7 - Section 4.2 - Explain the significance of a replication of the basal isotope anomaly. Does this indicate that the basal ice formed from precipitation during colder climatic conditions?

The significance of refinding the basal isotope anomaly lies in the fact that this supports the view of the basal ice not having undergone substantial changes over the last 25 years (i.e. since the anomaly was first described by Lorrain and Haeberli (1990)). We state this on page 9, Lines 11 ff. (revised manuscript). We also state that a full investigation of the origin of this anomaly is beyond the scope of this work. That said, as already discussed by Lorrain and Haeberli (1990), and also by Keck (2001) and Wagenbach et al. (2012), a pure atmospheric origin of this signal is very unlikely, with post-depositional processes probably contributing to this signature. We have added a more clear reference to this circumstance.

Changes to manuscript: P9, L8-9. Added statement.

P8- Figure 2 - Illustrate which samples have been obtained from the clear ice (cf. Figure1D/E).

Changed accordingly. Used grey shading in what is now Figure 3.

P8 - Again, a brief description of the ice facies and their key characteristics (e.g. debris content and bubble content) would help provide a context for the microstructural characteristics.

As discussed above we have followed this valuable suggestion and included a facies description in section 3.4 and Table 2, to which we again refer to here, especially regarding the clear basal ice of profile 1.

P9 - Figure 3 - Where have have these results been obtained from? “Selected results” rather than “exemplary results”.

Changed accordingly, we now provide this information in the caption of Figure 4.

P9 - Section 4.4 - Does progressive downwasting and thinning of the ice provide a potential explanation for the fall in temperature?

Interesting suggestion- after some consideration we would rather expect that thinning of the ice would allow atmospheric temperature variability to penetrate further into the ice, hence probably more likely associated with warming than cooling. Assuming that Lorrain and Haeberli measured the temperature only in the tunnel, not deeper in the walls of the ice (like we did), the two sets of reported temperature are not straightforward to compare. As we discuss in the manuscript, we believe that the englacial temperature measured in our vertical boreholes are to some extent the result of the artificial cooling of the tunnel. Another potential effect would be changes in surface energy balance by fabric cover and snow plowing (ski resort). However, it is difficult to disentangle these anthropogenic technical measures from natural effects. Without detailed measurements of energy fluxes, including latent fluxes, and refreezing/sublimation at the tunnel walls during several years, the potential effects cannot be quantified and explanations remain uncertain.
The certain and important consequence in the context of our work, however, is that the ice remains frozen to bedrock thus far.

P9 - L6 - Suggest rewording to - "...from basal temperature measurements revealing temperatures well below the pressure melting point"

Changed accordingly.

P10 - L6 - "karst" rather than "carst"

Changed accordingly.

P10 - L19/20 - Emphasise why a cold-based thermal regime is required to preserve old basal ice.

Changed accordingly. P13, L11ff.

P10 L19-22 - What is the source of this organic material and how has it been incorporated into the basal ice?

This is of course important- the organic material is assumed to be of eolian origin originally deposited on the glacier surface (like the dust-type layers visible in the stratigraphy). The basal layer, which contains a substantial amount of sediment from the bed, has been avoided for 14C analysis. We have included a statement to make this clear.

Changes to manuscript: P13, 17-18

P10 - L26-28 - What is the layering composed of? Variations in bubble content and ice crystal size? Suggestion here would be that this could be foliated ice in which case it could be illustrative of shear deformation.

We have clarified this and again referred to the new table with the ice facies characteristics. Given the regular nature of the layering parallel to the bed we interpret the layering as not supporting any signs of folding or stratigraphic disturbance, at least for the situation at profiles 1 and 2.

Changes to manuscript: Changes in section 3.4 and 4.3.

P10 - L29 - What is meant by the use of the term “dark”. Bubble free?

The term "dark" refers to the visual appearance of the layer with respect to the ambient ice. However, it is a result from larger amounts of dust in this layer, i.e. not from being bubble-free. We have clarified this in the new Table 2 and in section 3.4.

Changes to manuscript: P7, 6-7

P12- L6-7 - Earlier text suggested limited deformation whilst this suggests the potential for deformation - watch for possible contradictions here. Would typically expect significant shear strains in the basal ice layers of non-temperate glaciers frozen to hard rock beds.

Thank you for pointing out this possible ambiguity in reading this section, which we were not aware of. We state "that a moderate deformation is to be expected" in section 3.4 and, in this paragraph, that our findings in ice microstructure do not contradict the presence of shear deformation resulting from cold-based conditions. Having said that, in discussing the observed vertical gradient in age we are concerned with shear-introduced layer thinning, not turbulent ice flow. The latter is clearly not supported by the visual stratigraphy. We also discuss that the vertical age gradient could, as an alternative, also result from glacier growth interrupted by phases of stagnation or ablation and ultimately suggest further investigation. In this view, we do not see contradictions- however, we have reworded this section slightly to make our view more clear.

Changes to manuscript: P15, L1 ff.

P12 - L24-25 - Key finding - Give greater emphasis within the section.

Thank you for this suggestion. We have added text and elaborated on the paleoglaciological and paleoclimatological perspective on our key finding. As this work has been designed as a pilot study, final paleoclimatic interpretations will greatly benefit from a larger sample of measurements at various sites. The focus of this paper is to demonstrate the unchanged existence of the lowermost layers and their potential for drawing conclusions with the methods demonstrated applied to more locations.

Changes to manuscript: P15, L18-24 and P15, L28-32.

P13 - L5 - Suggest re-wording to: "Temperature measurements demonstrate basal temperatures that are well below the pressure melting point..."

Changed accordingly.

P13 - L9 - "...five ice blocks suggests a chronological order..."

Changed accordingly.

P13 - L14-15 - This final sentence is the key finding. Give greater emphasis (new paragraph?) and elaborate briefly on the potential palaeoclimatological and palaeoglaciological implications.

We have restructured this into a separate paragraph to further emphasize the significance of our key finding. In our view the main message is that although one site can only provide limited direct paleoclimatic insight, we have demonstrated the potential when extending this approach to other sites with greater geographic coverage in the Alps.

Changes to manuscript: P16, L15 ff.

References Hubbard, B. & Sharp, M., 1995. Basal ice facies and their formation in the Western Alps. Arctic & Alpine Research, 27(4), 301-310. Knight, P.G., 1997. The basal ice layer of glaciers and ice sheets. Quaternary Science Reviews, 16(9), 975-993.